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GEOLOGIC ANALYSES OF SELECTED APOLLO 10 70 mm LUNAR AND TERRESTRIAL PHOTOGRAPHS

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GREENBELT, MARYLAND

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ABSTRACT

This paper presents geologic analyses of selected Apollo 10 70 mm photographs taken during trans-lunar coast, lunar orbit, and trans-earth coast. Photographs of sinuous and non-sinuous rilles in Mare Tranquillitatis and northeastern Sinus Medii reveal X-shaped intersections and segments of rilles crossing hills, suggesting a basically tectonic rather than fluid flow origin. Detailed photographs of highland craters on the Moon's far side show mass-wasting that appears to have occurred by continuous flow, rather than in discrete slump blocks, which indicates a deep non-cohesive fragmental layer for such areas. Other photographs show mare ridges capped by higher-albedo hills that are apparently younger than the ridges, and which are thus suggested to be volcanic extrusions from the ridges. Several nearly-vertical photographs of Mare Smythii taken with high sun angles show dark-centered craters with bright walls, which may be of internal origin.

The color of the earth's surface can be seen with relatively little atmospheric distortion from distances of 30,000 miles or more, and enables recognition of a great amount of topographic detail in North Africa, south-west Asia, and North America. Brief descriptions of the major physiographic features visible on selected earth photographs are presented.

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GEOLOGIC ANALYSES OF SELECTED APOLLO 10 70 mm LUNAR AND TERRESTRIAL PHOTOGRAPHS

INTRODUCTION

The primary objective of the Apollo 10 mission was to provide the final engineering and telemetry data for lunar spacecraft evaluation prior to attempting the scheduled Apollo 11 lunar landing. Particular emphasis was placed on testing Lunar Module transportation, rendezvous, ejection and docking techniques in lunar orbit and monitoring required crew activities during the performance of these manuevers. To assist in attaining these objectives, the prime photographic requirement was to provide graphic documentation for each of the specific operational phases. Equipment included television, movie and still cameras with various lense, film and filter combinations. A detailed inventory and description of procedures is included in the Apollo 10 final Photographic and TV operations Plan (Nute, 1969), and is suggested reading for those interested in the total photographic activities.

In addition to providing engineering documentation, enough film was budgeted to permit long distance terrestrial and lunar photography during the translunar-transearth phases of the mission and to photograph the lunar surface. Lunar coverage included the locations of the several alternative proposed Apollo 11 landing sites and additional pre-selected areas which were chosen for their specific selenographic interest. By far the most interesting imagery for the selenologist was provided on the 70 mm film format of the hand-held Hasselblad EL cameras which were carried on both the command and lunar modules. Although all of the areas covered had been previously included in the near-vertical Lunar Orbiter photography, the 70 mm format provides perspectives which differ both in lighting and obliquity, and provide variations which locally enhance the observation capability of specific lunar features. In addition, the entire content of a frame can be viewed without the necessity of compensating for the distortions inherent in the reassembled Orbiter framelets. With these differences in mind, selected Apollo 10 photographs can provide significant additional information for the study of lunar morphology. Several preliminary geological analyses of a few of these pictures will now be considered.

ORIGIN OF SINUOUS RILLES

The theory that sinuous rilles, such as Schroter's Valley, are the result of erosion by running water has recently received considerable attention (Urey, 1967; Lingenfelter, et al., 1968; Gilvarry 1968; Muller and Sjogren, 1969; and others). Competing theories include formation by flow of lava, as drainage channels (Strom, 1966), formation by tectonic subsidence, perhaps accompanied by maar eruptions (as along Hyginus Rille) (Hackman, 1966), by collapse of lava tubes (Oberbeck, et al., 1969) or nueés ardentes (Cameron, 1964). These theories are summarized by Cameron (1967) and Lowman (1969). It should be noted that formation by simple down-faulting (i.e., graben subsidence) is generally accepted for relatively straight, shallow rilles with nearly parallel walls, and especially those which cut across hills ("normal" rilles in Cameron's (1967) classification).

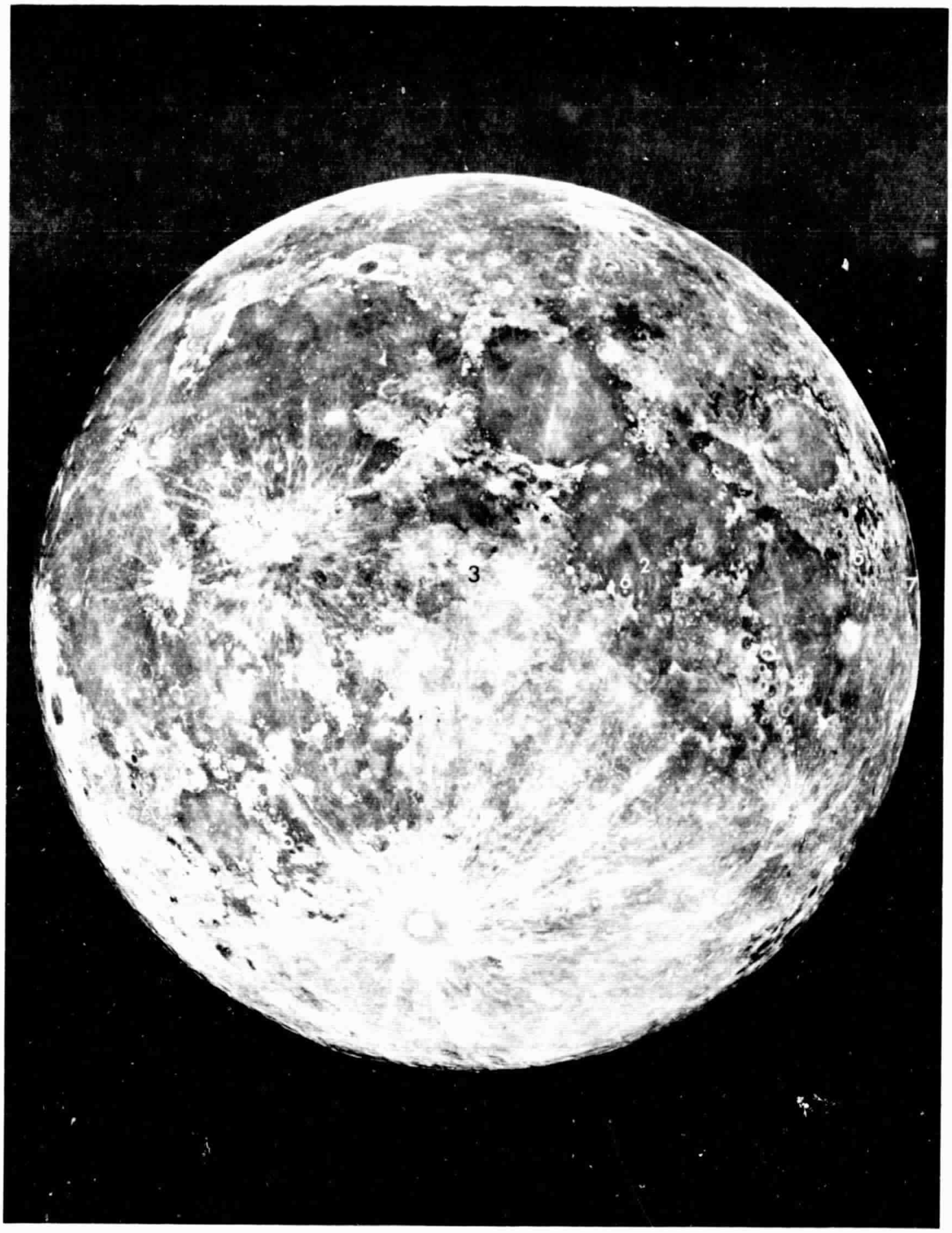

Figure 1. Location of figures on near side of the moon. Figures 4A and 4B are at 158°E, 06°S and 133°E, 0.6°N respectively, on the far side.

Several Apollo 10 photos appear useful for the study of sinuous rilles, and two of these are shown in Figures 2 and 3. Both show several X-shaped intersections of sinuous and non-sinuous rilles, which Cameron (1964) suggested were indicative of a tectonic origin. In Figure 3, however, we find even more definite support for a non-erosional origin.

It will be noted that there is a typical sinuous rille just below and left of the carter Ukert, which provides a convenient model with which to compare other rilles in the area. There is a similar rille north of Ukert (see arrow). The non-erosional nature of this rille is demonstrated by the fact that it clearly crosses a ridge of a Fra Mauro material. Although such dissected ridges are common on earth, they are generally the result of either drainage superposition or uplift of a ridge slowly enough to permit a down-cutting stream to keep pace (antecedent drainage). Both processes, as well as simple selective erosion, can be ruled out on the moon, since they involve long-continued subaerial erosion. In addition, the pre-mare age of the Fra Mauro material independently rules out antecedent drainage, since the rille is post-mare. Further though more indirect evidence for non-erosional origin for this sinuous rille comes from its close association with the rest of the Triesnecker rille system. The essentially tectonic nature of this system is suggested by the X-intersections, disconnected en echelon segments, and by the general straightness and shallowness of many segments. In addition, closeness of this rille to the Hyginus rille suggests that volcanism may also have played some part in its origin; Lowman (1969) has

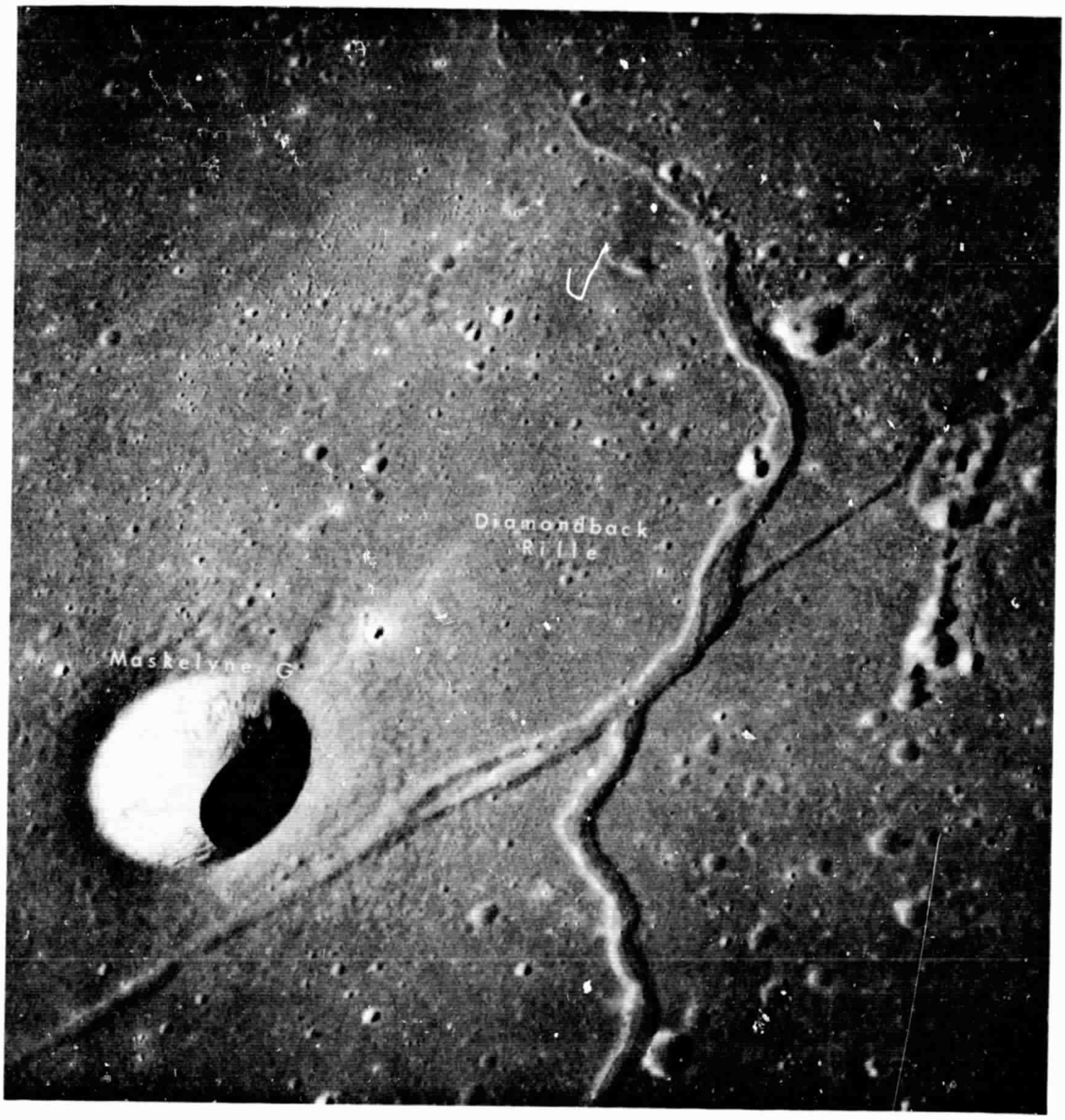

Figure 2. "Diamondback" Rille. This rille system has characteristics of both straight and normal rilles. The distinctive X-shaped intersection where the two rilles cross provides evidence against fluvial origin.

Figure 3. Triesnecker rille system. Rille cutting highlands (arrow) supports the concept of non-erosional origin for sinuous rilles. Chain craters along Hyginus rille are considered an example of volcanic activity localized by rilles.

suggested that sinuous rilles in general grade into "normal" rilles, and proposed that they are subsidence features along fractures, accompanied in some places by largely gaseous volcanic eruptions. Figure 3 appears to support such an interpretation.

SUBSURFACE STRUCTURE OF HIGHLANDS (TERRAE)

Several of the Apollo 10 70 mm photos show in detail the fine structure of highland craters on both the near and far sides of the Moon, and these provide excellent examples for comparison with the many mare craters which were extensively photographed during the mission. It appears that highland craters are especially favorable for the occurence of landslides on the inner flanks, using the term "landslides", following Terzaghi (1950), to mean the downslope movement of a relatively small body of material with well-defined boundaries, with no implication as to speed of movement. Furthermore, these slides are commonly composed of many thin slabs, or slices (Figure 4), in contrast to the relatively wide blocks forming the inner walls of craters such as Copernicus (formed in a mare area). Parts of several slides in highland craters have apparently flowed en masse, rather than as discrete blocks. The appearance of the slides in the highlands, especially on the far side, suggests a rather low shear strength of the material, which would be consistent with the theory that the highlands are a very deep layer of fragmented rock. Such slides are relatively uncommon in craters of similar size in the maria, supporting the further inference that the maria

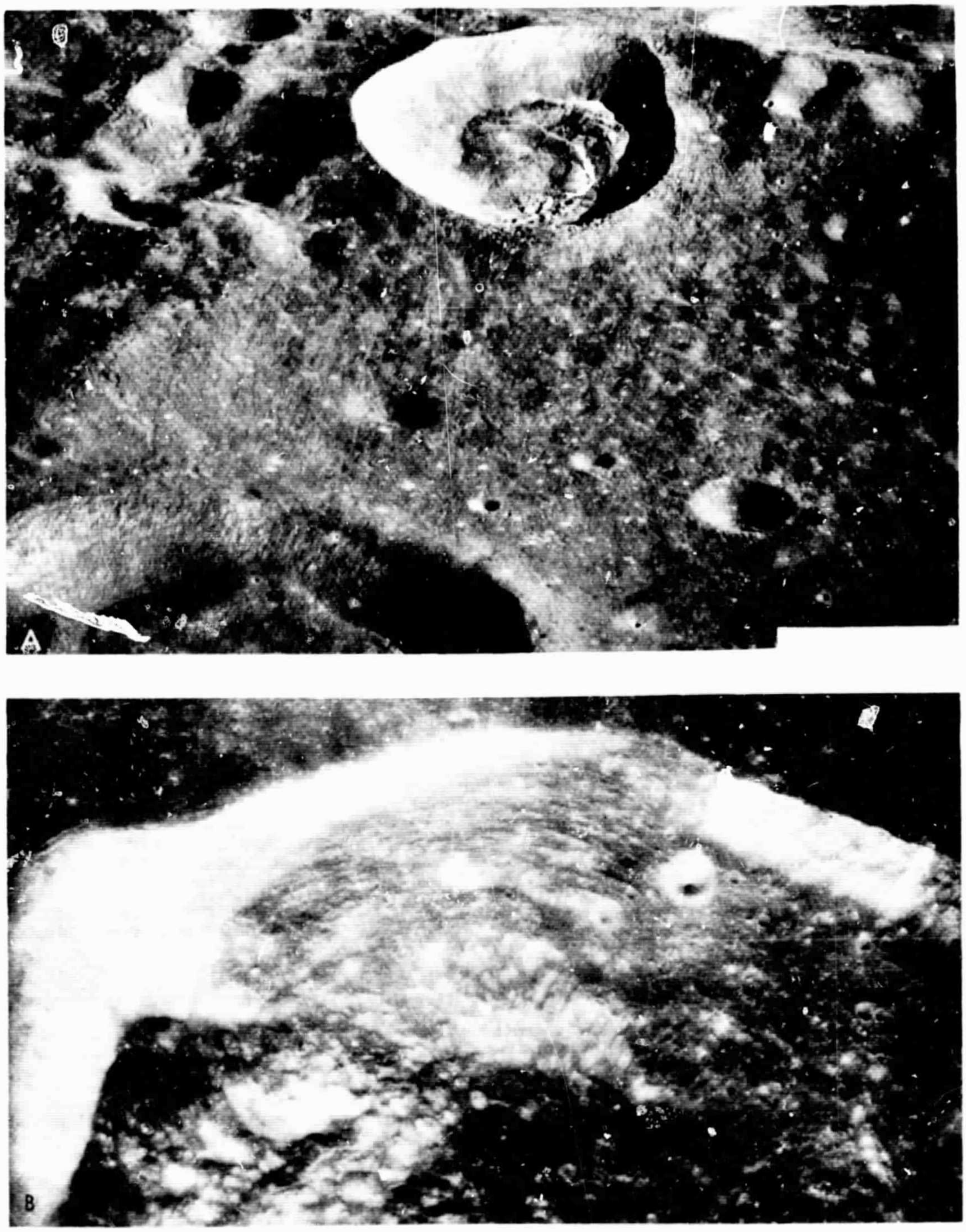

Figure 4. A. Highland crater on lunar far side shows occurrence of landslides on the inner crater flanks. B. This type slide, which is commonly associated with farside highland craters, is commonly composed of many thin slabs or slices which appear to have flowed en masse rather than as discrete blocks.

consist of one or more layers of relatively solid rock overlain by up to several meters of unconsolidated debris (Whitaker, 1966; Anon., 1967; Wade and Blodget, 1967; Oberbeck and Quaide, 1968, and others).

Additional evidence for the fragmental subsurface structure of the highlands is also recognized in Figure 5. This 3 to 4 km wide, very bright ray crater is on the west edge of Mare Spumans, a small mare in the highlands near the eastern limb. The inner walls of the crater appear to be loose fragmental material, perhaps at the maximum angle of repose, with little evidence of solid bedrock, such as stratification. Furthermore, this fragmental layer is probably not the result of long-term mass wasting, because the brightness of the ray system indicates that the crater is relatively young. It would appear that if the crater had been formed in solid bedrock, diagnostic evidence would be discernable; at Meteor Crater, Arizona, for example, roughly one-third of the inner wall is exposed solid bedrock, even though Meteor Crater has already undergone a relatively high degree of erosion and mass wasting. Relatively young mare craters, furthermore, frequently show concentric terraces, as demonstrated by Oberbeck and Quaide (1968).

This interpretation is tentative and further study is required to confirm the conclusion. A comparison of mare and highland craters of similar age and size in several areas should provide the necessary evidence.

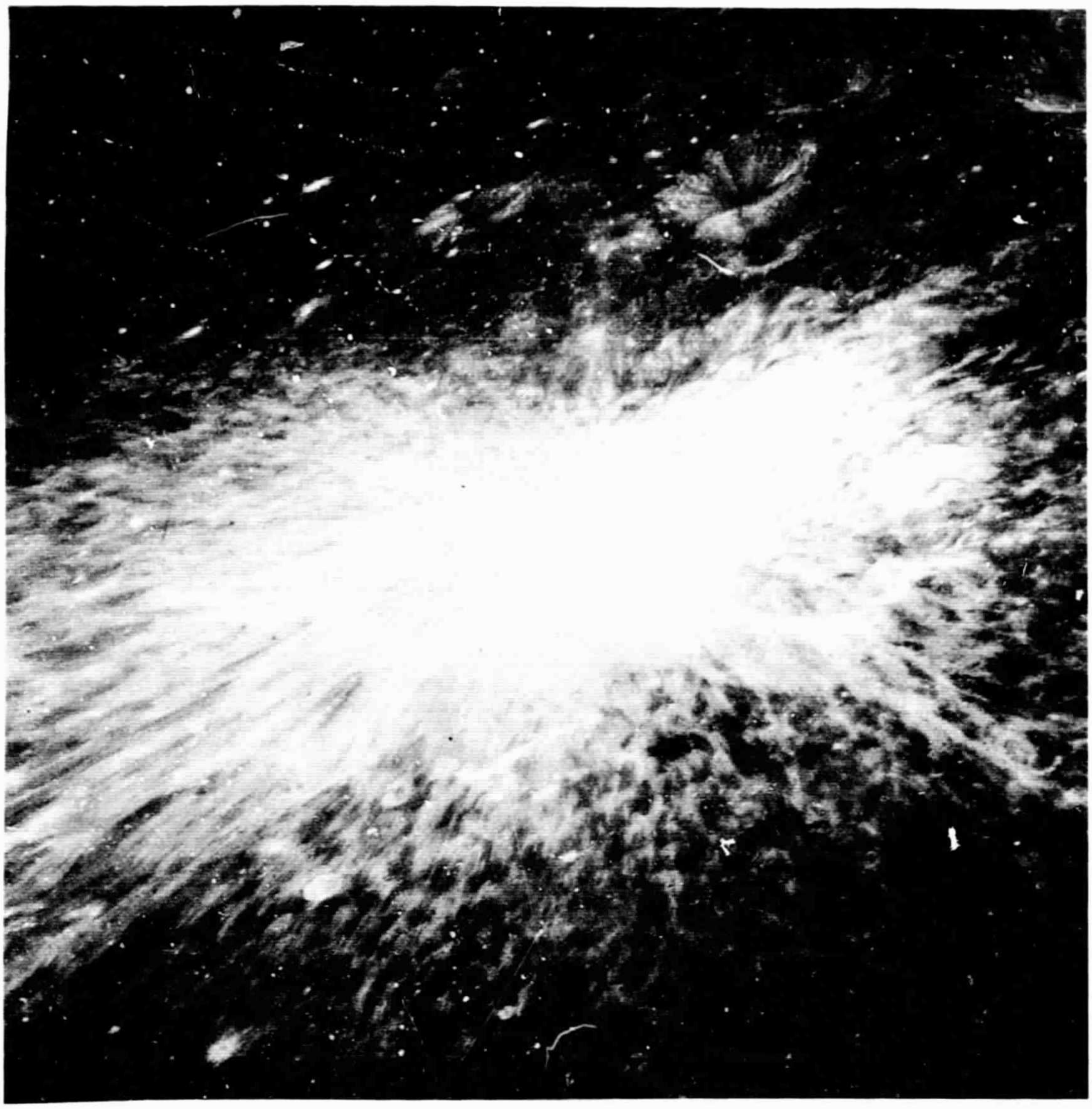

Figure 5. Bright ray crater on west edge of Mare Spumans. The inner crater walls appear to be loose fragmental material, and there is little evidence of solid bedrock.

ORIGIN OF MARE RIDGES

Despite their widespread occurrence, the nature of the mare ridges is not well understood. One theory alleges that they are the surface expression of fissures along which the volcanic material of the maria was erupted (Hackman, 1966). This, and the alternative theories, which include differential compaction, folding and horst-type faulting and are reviewed by Lowman (1969a). At least one of the Apollo 10 pictures includes the good examples first noticed in Lunar Orbiter photos to support first-mentioned theory (Figure 6). The light-colored small hills (see arrows) cap the ridges in at least two places and at the same time do not seem to be affected by the ridge trends. Thus the position of the capping materials strongly indicates that they are younger than the ridges. This relationship is difficult to explain if the ridges are instead, interpreted to be folds or faults. However, it is consistent with the intrusion theory, which holds that in certain cases, a relatively late surge of magma breaks through the ridges to erupt on the surface.

INVESTIGATION OF ANOMALOUS CIRCULAR FEATURES

The nearly vertical photographs AS 10 28-4153 to 4159 show a curious class of bright, ringshaped markings on Mare Smythii (Figure 7). On the original 70 mm format, the majority have outer diameters between 200 microns and 2 millimeters. Since the scale of the photography is approximately 1:1,000,000 at this point, the true diameters of these objects vary from 200 to 2000 meters.

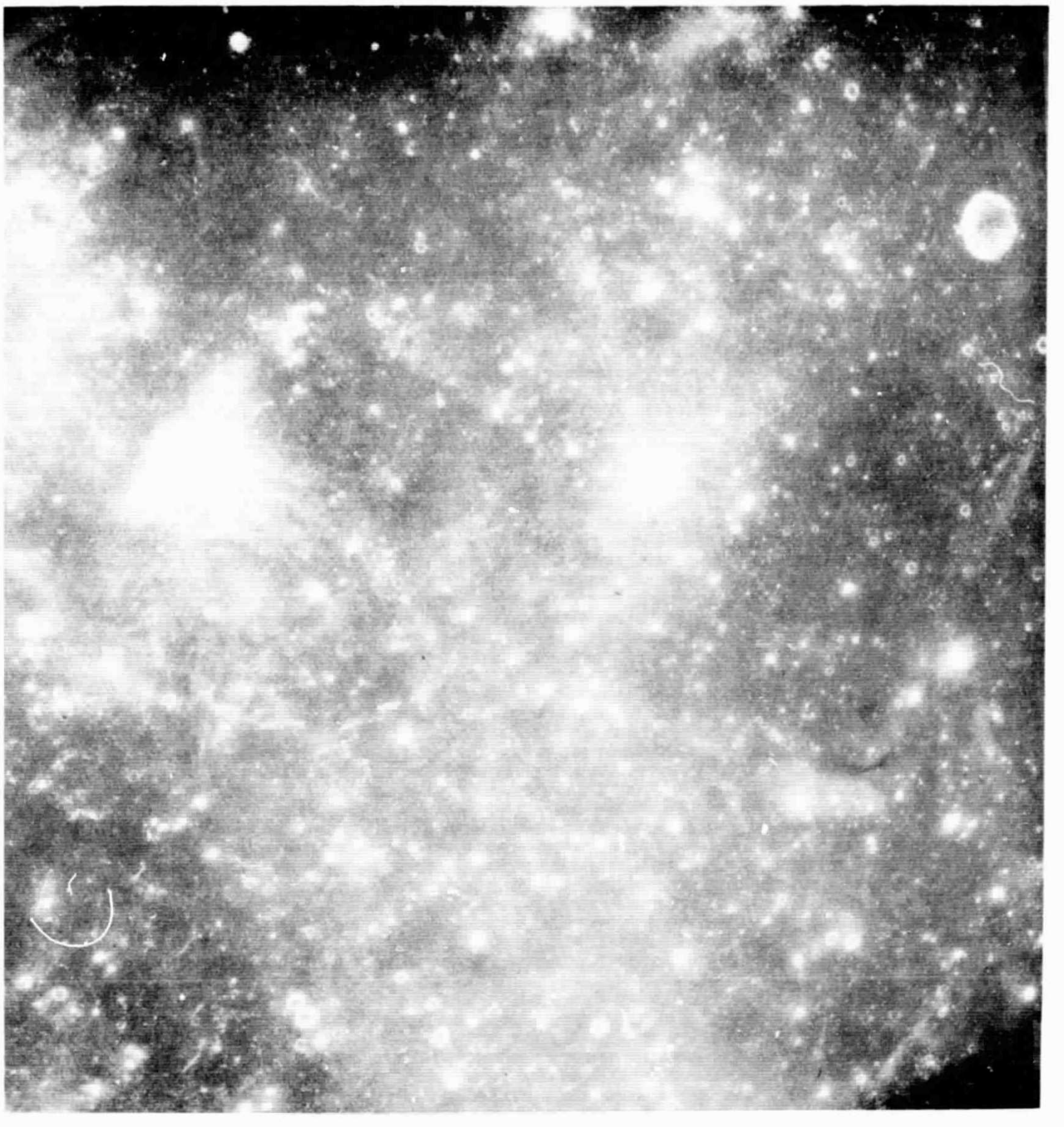

Figure 7. Mare Smythii. The many dark-centered craters, which are readily distinguished from small, similar-sized ray craters, may have been formed by a process other than impact.

The inner dark center has a diameter usually slightly less than half the outer diameter, or from 80 to 800 meters. The phase angle in Mare Smythii at the time of exposure was small, so that shadows are not visible, and the objects are seen by backscattered light.

The dark-centered craters lack rays, and can be distinguished easily from the rarer ray craters, which are also seen in the photography of Mare Smythii. Both the inner and the outer circumference are approximately symmetrical, contrasting with the irregular outline of the ray craters. The centers of the ray craters, though not always quite as bright as the rim, are normally brighter than the background. Ray craters tend to be brighter than dark-centered craters.

In about half of the small dark-centered craters, there are dark spokes which radiate from the center across the bright material. By comparison with similar features clearly visible on larger craters, it seems likely that the spokes represent streaks on the walls of the crater caused by mass wasting down the wall. The slopes on which this occurs are therefore presumably at an angle near the angle of repose of the material, or around 40°.

The dark-centered craters are apparent only on mare surfaces or in craters which appear to be floored with mare material.

One explanation for the appearance of the dark-centered craters may be that they are old ray craters (i.e., of impact origin) whose inner slopes have been brightened by mass wasting. This phenomenon, though not understood, is well known in other parts of the Moon. Geologists such as R. J. Hackman (1966) who have mapped parts of the Moon under the USGS/NASA mapping program, commonly find steep slopes to be higher in albedo than surrounding material of similar age, and attribute this to exposure of fresh rock by mass wasting. However, alternative explanation appears possible for the dark-centered craters.

W. S. Cameron and G. Coyle (1969) have drawn attention to a class of craters noted on Orbiter photography, which have boulders only within the crater, and which might conceivably be related to the dark-centered craters noted here. They also recognize that these craters are morphologically distinct from typical fresh impact craters for they are more symmetrical and less rough. Since boulders often have lower albedo than the surrounding soil, and since this difference is visible at zero phase, as was clear from the Surveyor photography, it is suggested that the dark-centered craters may be similar to those described by Cameron and Coyle, and seen near zero phase.

If the dark-centered craters are distinct from the ray craters, then it seems possible that the dark-centered craters may not be of impact origin, since the impact origin of the ray craters is generally admitted. It thus appears that among the small bright craters on the maria, (diameters from 200 meters to 2 km) the majority may not be of impact origin, since the dark-centered craters outnumber the ray craters by about 6 to 1, in this size range, and since there is no reasonable doubt about the impact origin of the ray craters. This does not, however, necessarily mean that the dark-centered craters are being formed as abundantly as the ray craters, since there may be sliding on the walls of the dark-centered craters, as discussed above.

On the other hand, the large number of non-impact craters on the maria, especially for diameters less than 500 meters, fits with the fact that on the maria, there are more craters between 50 and 500 meters in diameter, than on the highlands, though the number of telescopic craters on the highlands is 10 times that on the maria, in general. It appears possible that some non-impact process may have produced a large number of craters in this range. If this is the case, then the estimates of the age of the maria based on crater counts in this size range are too large.

DEEP SPACE EARTH PHOTOGRAPHY

In addition to the high-quality lunar photographs, the Apollo 10 flight provided several exceptional series of small scale photographs of the earth taken from altitudes of 30,000 miles and more. These include pictures which show large cloud-free areas of North Africa, southwest Asia and also North America. Several of these have been studied in some detail to determine the effects of extreme altitude on color recognition, resolution and the ability to recognize regional geological features.

Most of the predominantly desert area of North Africa and the Middle East (Figure 8) has been previously photographed during the manned Mercury and Gemini and Apollo earth-orbiting missions, and these larger-scale synoptic views have provided significant new geologic information (Lowman 1969b, and others). The abundance and high quality of the pictures is, of course, due to the

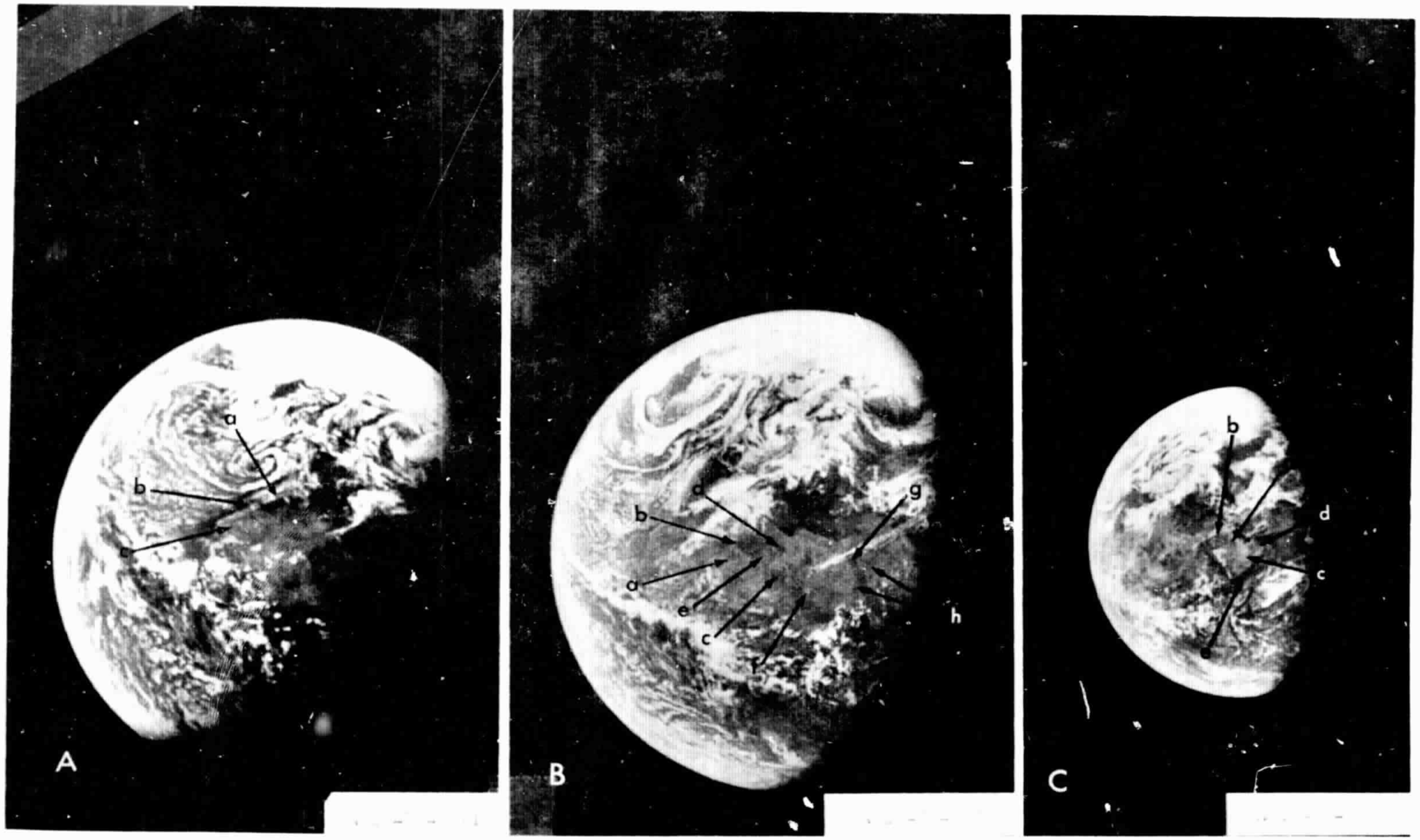

Figure 8. Deep space earth photography of North Africa and southwest Asia. Many of the regional geologic units can be recognized even though the imagery was obtained at altitudes greater than 30,000 miles. A. a. Atlas mountains, b. south Atlas line, and c. Dorsale Reguibat, B. a. Ahagger uplift, b. Tassili n'agger, c. Tibesti mountains, d. Haruj al Aswud, e. Marzuk sand sea, f. Khufra basin, g. Red Sea and h. Arabo-Nubian Precambrian shield. C. a. Dahna dune trend, b. Nafud desert, c. rub al Khali basin, d. Oman mountains and e. Gulf of Aden.

general year around paucity of cloud coverage and the limited atmospheric dispersion over this entire intercontinental area.

Literally dozens of major geological features are discernable on the deep space photos, but only a few of the larger units will be briefly considered here. The complexly folded Atlas mountains of Morocco are clearly visible on Figure 8A. The southern border of the High and Sahara Atlas ranges adjoins the older, more stable shield areas along the distinctive South Atlas line. Further south, the Dorsale Reguibat is recognized by its characteristic suboval shape. When the second series of pictures was obtained, this portion of northwest Africa was cloud-covered, but eastward the latter sequence provided more clear coverage of the major physiographic units of the Sahara (Figure 8B). The darker areas include the Ahaggar uplift, Tassili n'ajjer, Tibesti mountains and the lava flows of the Haruj al Aswad. Two of the great basins of the central Sahara, the Marzuk sand sea and the Khufra basin, appear as sub-circular depressions and are distinctly recognizable south of the Sirte Gulf (Figure 8B). As the spacecraft moved eastward, the entire Arabian peninsula came into view (Figure 8C). The Arabian peninsula, which is geologically more closely related to Africa than to Asia, includes the western part of the Arabo-Nubian shield. This Precambrian complex was divided by the structural formation of the Red Sea during Miocene time, and forms much of the dark areas present on both sides of the Red Sea. On the Arabian peninsula, the sedimentary beds dip gently outward from the shield: eastwardly to form part of the oil-rich Persian Gulf oil province and south and southeastward into the ar Rub al Khali basin. The subtle tonal changes on the color imagery show that the sedimentary outcrops roughly parallel the limits of the shield complex. The thin, darker-colored band located to the east of the consolidated sedimentary outcroppings is the linear Dahna dune trend which extends northwestward into the similarly colored Nafud desert of Saudi Arabia. This distinctive hue on the color photography, and to a lesser extent in the black and white photos thus can distinguish, on a gross scale, surficial sands which have been derived from different source areas. The dark areas of the southeastern Arabia peninsula are the broadly uplifted Oman mountains, which consist of igneous and sedimentary rocks of predominantly Permian and Mesozoic age.

Structurally the Red Sea and Gulf of Aden form part of the world rift system, and the near-parallelism of the opposing coasts can be readily recognized (Figures 8B & C). This parallelism has led to the assumption by many that these water bodies were formed as the result of continental drifting associated with large wrench-type fault displacements (Carey 1958, and others). Although the geography is admittedly somewhat distorted, the photos still clearly show that if the Arabian peninsula were to be restored to its supposed corresponding place along the matching African coast line, the Somali and Aden coasts would not be properly matched. More detailed studies at larger scales, which match the continental shelves rather than the shore-lines, fail to produce a significantly better union than that which can be visualized from these photographs (United Nations, 1963). Thus, a more sophisticated model is required to fit the observations (Gass, et al., 1969).

In the western hemisphere (Figure 9) the cloud-free areas include most of the southwest United States and a north-trending strip in the central and southern U. S. Although resolution is extremely poor, a number of terrain features can still be recognized by various characteristics. The Sierra Nevada mountains can be recognized from the overhanging clouds and/or snow cover, while the Mojave desert can be discerned by the dark tone of the bounding mountains. The San Andreas and Garlock faults form the boundaries of Mojave Desert on west and north, and are thus recognized in this area, but cannot be distinguished elsewhe. . Irrigated farm land on the Colorado River delta is recognized on its distinctive dark color, and just to the northwest, the Salton Sea distinguishable by a combination of dark color and distinctive shape.

The ground resolution near the center of the picture is probably around 10 miles for high-contrast features, since the narrow part of the Salton Sea can be resolved.

The colors shown on this and similar pictures are extremely interesting, because the pictures are nearly vertical, and hence the effects of the atmospheric scattering, which are proportional to the cosine of the tilt, on color are minimized. The Basin and Range Province appears chiefly buff and the Colorado Plateau a reddish brown, with the high mountains indefinite dark colors. Of greater interest is the sharp color change, to a dark olive green, in the southern and central parts of the United States. This is probably the expression of the much denser vegetation in these areas, as well as the atmospheric humidity (and consequent scattering). This color appears to be a relatively permanent characteristic

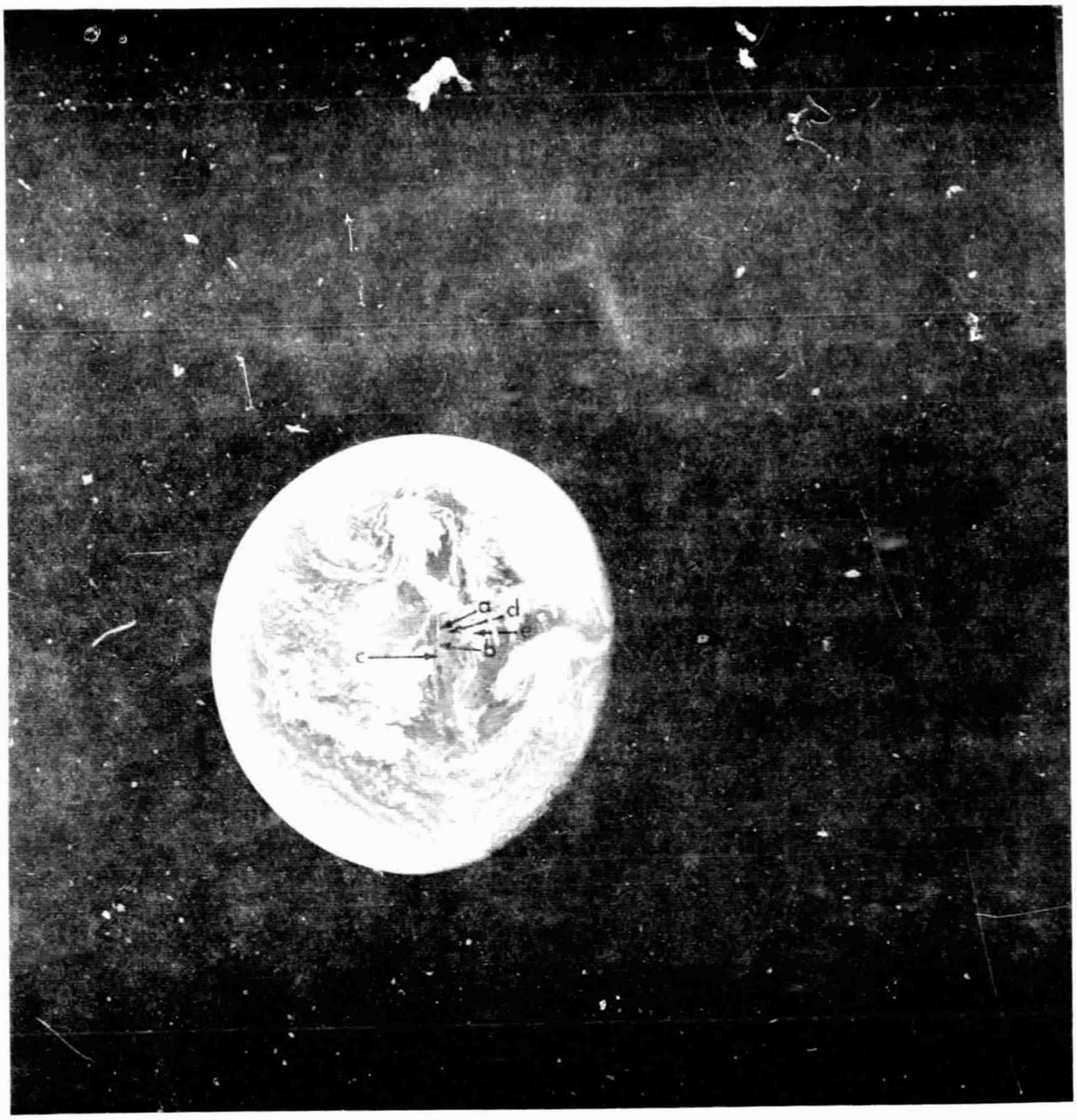

Figure 9. Deep space earth photography of North America. Some of the major geologic features which can be identified include a. Sierra Nevada mountains, b. Mojave desert, c. Salton sea, d. Basin and Range Province and e. The Colorado plateau.

since it is also visible on earth photographs taken on later days of the mission. This suggests that it is chiefly vegetation. Similar dark olive green colors can be seen in Spain, Turkey, and parts of southwest Asia. Care must be used in color interpretation, however, since colors near the teminator tend to fade into blue-green.

In summary, it has been shown that despite the very small scale, these terrestrial photos are of adequate resolution to show many of the major regional geologic interrelationships, and also some generalized botanical distribution information. The amazing amount of information which can be derived from this ultra-small scale imagery leads to great optimism for the productiveness of the proposed ERTS program which will yield vidicon imagery from much lower altitudes with significantly higher resolution.

ACKNOWLEDGMENTS

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